Astrophysical Evidence for Black Holes*

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Abstract

The case for collapsed objects in some X-ray binary systems continues to strengthen. But there is now even firmer evidence for supermassive black holes in galactic centres. Gravitational collapse seems to have occurred in the centres of most newly-forming galaxies, manifesting itself in a phase of quasar-like activity (which may be reactivated later). These phenomena (especially the gas-dynamical aspects) are still a daunting challenge to theorists, but there is 'cleaner' evidence, based on stellar dynamics, for collapsed objects in the centres of most nearby galaxies. The current evidence does not tell us the spin of the collapsed objects – nor, indeed, whether they are described by Kerr geometry, as general relativity theory predicts. There are now, however, several hopeful prospects of discovering observational signatures that will indeed probe the strong-gravity domain.

1 Introduction

It's fitting to start with a text from Chandrasekhar (1975): "In my entire scientific life .... the most shattering experience has been the realisation that an exact solution of Einstein's equations of general relativity, discovered by the New Zealand mathematician Roy Kerr, provides the absolutely exact representation of untold numbers of massive black holes that populate the Universe."

When Chandra wrote this, the evidence was still controversial (see Israel 1996) : belief in black holes was at least partly an act of faith (defined by St Paul as 'the substance of things hoped for: the evidence of things not seen'). But observational progress has been remarkable, especially within the last couple of years.

I shall first address the question: Do massive collapsed objects exist – stellar-mass objects in binaries; and supermassive objects in the centres of galaxies?

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The evidence points insistently towards the presence of dark objects, associated with deep gravitational potential wells; but it does not in itself tell us about the metric in the innermost region where Newtonian approximations break down.

The second part of this paper addresses a separate question: Do these objects have Schwarzschild/Kerr metrics? Several new observational probes of the strong-field domain close to the hole have recently become feasible, offering real prospects of crucially testing our theories of strong-field gravity.

2 Stellar-mass black hole candidates

It was recognised back in the 1960s that X-ray sources in binary systems, fuelled by the accretion of gas captured from a companion, would be black hole candidates if they displayed rapid irregular flickering, and if the inferred mass were too high for them to be conventional neutron stars. The likelihood of such stellar-mass remnants was of course prefigured by Chandra's classic early work.

The discovered systems divide into two categories: those where the companion star is of high mass, of which Cyg X 1 is the prototype; and the low-mass X-ray binaries (LMXBs), where the companion is typically below a solar mass. The LMXBs are sometimes called 'X-ray novae', because they flare up to high luminosities: they plainly have a different evolutionary history from systems like Cyg X1. The prototype of this class is A 0600-00, discovered in 1975. At least 5 further LMXBs have been discovered more recently, and have had their masses estimated; other galactic X-ray sources are suspected, on spectroscopic and other grounds, to be in the same category. The strongest current candidates are listed in Table 1, adapted from Charles (1997). Fuller discussion of these systems, and the evolutionary scenarios that might lead to them, are given by Tanaka and Lewin (1995) and Wijers (1996).

None of these black hole candidates displays the kind of regular period that is associated, in other systems, with a neutron star's spin rate. Indeed it is gratifying that, as discussed in John Freedman's contribution, the putative neutron stars all have masses clustering around $1.4 M_\odot$, and there are no regularly-pulsing X-ray sources with dynamically-inferred masses much higher than this. However, some of the high-mass sources display interesting quasi-periodicities which (as discussed later) may offer probes of the metric.

Of course the only black holes that manifest themselves as conspicuous X-rays sources are the tiny and atypical fraction located in close binaries where mass transfer is currently going on. There may be only a few dozen such systems in our Galaxy. However, there is every reason to suspect that the total number of stellar-mass holes is at least 10^7. This is based on the rather conservative estimate that only one or two percent of supernovae leave black holes rather than neutron stars. Still larger numbers of holes could indeed exist (maybe even in the Galactic Halo) as relics of early galactic history.

3 Supermassive holes

Even at the first 'Texas' conference, held in 1963 when quasars had just been discovered, some theorists were suggesting that gravitational energy, released by a supermassive object, was responsible for the powerful emitted radiation. There has been a huge (and increasingly systematic) accumulation of data on quasars, and on the other classes of active galaxies which are now recognised as being related: the Seyfert galaxies, already noted as a distinctive category 50 years ago, and the strong radio galaxies (known since the 1950s). But our understanding has developed in fits and starts. Even if a convincing explanation has eventually emerged, it sometimes seems as though this happened only after every other possibility had been exhausted.

Recent progress in the study of active galactic nuclei (AGNs) brings into sharper focus the question of how and when supermassive black holes formed, and how this process relates to galaxy formation. Even more important has been the discovery of ordinary galaxies with equally large redshifts: these were until recently too faint to be detected, but can now be studied with the combined resources of the Hubble Space Telescope (HST) and the Keck 10-metre telescope. But the most clear-cut and quantitative clues have come from studies of relatively nearby galaxies: the centres of most of these display either no activity or a rather low level, but most seem to harbour dark central masses. I shall summarise this evidence, and then outline how it fits in with the broad picture of galaxy formation and evolution that is now coming into focus.

3.1 Evidence from the stellar cusp – M31 (Andromeda) and others

Central dark masses – dead quasars – have been inferred from studies of the the spatial distribution and velocities of stars in several nearby galaxies (see Kormendy and Richstone, 1995; Tremaine, 1997; or van den Marel, 1996 for recent reviews). There is, for instance, strong evidence for a mass of about $3 \times 10^7 M_\odot$ in the centre of Andromeda (M31). Even in such a nearby galaxy as this, the hole's gravitational effects on surrounding stars are restricted to the central 2-3 arc seconds of the galaxy's image. Higher-resolution data from the post-refurbishment HST should crucially clarify what is going on in these systems. A list of the candidates (as of January 1997) is given in Table 2.

3.2 M87: low-level activity and a supermassive hole

Although M87, in the Virgo Cluster, was the first in which a tightly-bound stellar cusp was claimed (Sargent *et al.* 1978; Young *et al.* , 1978), the stellar-dynamics in the core of this giant elliptical galaxy even now remains rather ambiguous. According to Merritt and Oh (1997) the data are consistent with a central mass of $(1-2)10^9 M_\odot$, but the radial dependence of the projected

densities and velocities could be accounted for by a dense stellar core alone, provided that the velocities were suitably anisotropic. Separate evidence for a dark central mass comes, however, from a disc of gas, orbiting in a plane perpendicular to the well-known jet (Ford *et al.* 1994). One of the complications in studying the central stars in M87 is that the nucleus is not quiescent, but that the inner part of the jet emits non-thermal light as well as radio waves.

X-ray data reveal hot gas pervading M87 itself, as well as in the surrounding cluster. If there were a huge central hole, then some of this gas would inevitably be swirling into it, at a rate that can be estimated. This accretion would give rise to more conspicuous activity than is observed if the radiative efficiency were as high as 10 per cent. Fabian and Canizares (1988) were the first to highlight this apparent problem with the hypothesis that elliptical galaxies harbour massive central holes. Actually, the quiescence is less surprising because, for low accretion rates, the expected luminosity scales as $\dot{M}^2$ rather than as $\dot{M}$: when accretion occurs at a low rate, and the viscosity is high enough to ensure that the gas swirls in quickly (so the densities are low), the radiative efficiency also is low. The gas inflates into a thick dilute torus,where the kinetic temperature of the ions is close to the virial temperature. Only a small fraction of the binding energy gets radiated during the time it takes for each element of gas to swirl inward and be swallowed. Bremsstrahlung, in particular, is inefficient in this situation; the most conspicuous emission may be in the radio band, resulting from synchrotron emission in the strong magnetic field in the inner part of the accretion flow. The radio and X-ray emission is actually fully consistent with accretion at the expected rate, so the observed non-stellar output from M87 actually corroborates the other evidence for a supermassive hole. (Fabian and Rees, 1995; Narayan and Yi 1995; Reynolds *et al.* 1996; Mahadevan 1997; and references cited therein).

Weak central radio sources are found in the centres of surprisingly many otherwise quiescent ellipticals (Sadler *et al.* 1995 and references cited therein). If these galaxies all harbour massive holes, this emission could similarly be attributed to accretion in a slow, inefficient, mode (Fabian and Rees 1995)

3.3 The remarkable case of NGC 4258

Much the most compelling case for a central black hole has been supplied by a quite different technique: amazingly precise mapping of gas motions via the 1.3 cm maser-emission line of H_2O in the peculiar spiral galaxy NGC 4258 (Watson and Wallin 1994; Miyoshi *et al.* 1995) which lies at a distance of about 6.5 Mpc. The spectral resolution in the microwave line is high enough to pin down the velocities with accuracy of 1 km/sec. The Very Long Baseline Array achieves an angular resolution better than 0.5 milliarc seconds (100 times sharper than the HST, as well as far finer spectral resolution of velocities!). These observations have revealed, right in the galaxy's core, a disc with rotational speeds following an exact Keplerian law around a compact dark mass. The inner edge of the

observed disc is orbiting at 1080 km/sec. It would be impossible to circumscribe, within its radius, a stable and long-lived star cluster with the inferred mass of $3.6 \times 10^7 M_\odot$. The circumstantial evidence for black holes has been gradually growing for 30 years, but this remarkable discovery clinches the case completely. The central mass must either be a black hole or something even more exotic.

NGC 4258 poses several puzzles. What determines the sharp inner edge of the 'masing' disc? What is the significance of its inferred tilt and warping? How does this thin disc relate to the (thicker) 'molecular tori' that have been postulated in Seyfert galaxies? All these questions deserve study. It would help, of course, if other similar discs could be found. Another Seyfert galaxy, NGC 1068, may show resemblances, but NGC 4258 may prove to be an unusually fortunate example, because its disc is viewed almost edge-on.

3.4 Our Galactic Centre

Most nearby large galaxies seem to harbour massive central holes, so our own would seem underendowed if it did not have one too. There has been theoretical advocacy of this view for many years (eg Lynden-Bell and Rees 1971). Also, an unusual radio source has long been known to exist right at the dynamical centre of our Galaxy, which can be interpreted in terms of accretion onto a massive hole (Rees 1982; Melia 1994; Narayan, Yi and Mahadevan 1995). But the direct evidence has until recently been ambiguous (see Genzel,Townes and Hollenbach, 1995 and earlier work reviewed therein). This is because intervening gas and dust in the plane of the Milky Way prevent us from getting a clear optical view of the central stars, as we can in, for instance, M31. A great deal is known about gas motions, from radio and infrared measurements, but these are hard to interpret because gas does not move ballistically like stars, being vulnerable to pressure gradients, stellar winds, and other non-gravitational influences.

The situation has, however, been transformed by remarkable observations of stars in the near infrared band, where obscuration by intervening material is less of an obstacle (Eckart and Genzel 1996). These observations have been made using an instrument (ESO's 'New Technology Telescope' in Chile) with sharp enough resolution to detect the transverse ('proper') motions of some stars over a three-year period. The radial velocities are also known, from spectroscopy, so one has full three-dimensional information on how the stars are moving within the central 0.1 pc of our Galaxy. The speeds, up to 2000 km/sec, scale as $r^{-1/2}$ with distance from the centre, consistent with a hole of mass $2.5 \times 10^6 M_\odot$.

In my opinion our Galactic Centre now provides the most convincing case for a supermassive hole, with the single exception of NGC 4258.

3.5 The cumulative evidence

A summary of the current evidence is given in Table 2. The data here (as in table 1) are developing rapidly, and the list may well be longer by the time this

paper appears in print.

A feature of the data in this table, emphasised by Kormendy and Richstone (1995) and by Faber *et al.* (1997), is a crude proportionality between the hole's mass and that of the central bulge or spheroid in the stellar distribution (which is of course the dominant part of an elliptical galaxy, but only a subsidiary component of a disc system like M31 or our own Galaxy.) This conclusion is only tentative, being vulnerable to various selection effects, but it suggests that the hole may form at the same time as the central stellar population. In section 5 I shall briefly discuss formation scenarios for the holes, in the context of the remarkable recent progress achieved by optical astronomers in probing the era when galaxies were still forming.

4 The fate of stars near a supermassive hole

4.1 Tidal disruption

Even if a galaxy's core were swept so clean of gas that no significant emission resulted from steady accretion, there is a separate process that would inevitably, now and again, liberate a large supply of gas whenever a supermassive hole was present: tidal disruption of stars on nearly radial orbits. A rough estimate, based on models for the stellar distribution and velocities, suggests that in M31 a main-sequence star would pass close enough to the putative hole to be tidally disrupted about once every 10^4 years. These estimates, for M31 and other nearby galaxies, should firm up when post-refurbishment HST data are available: it is a stellar-dynamical (rather than gas-dynamical) problem, and therefore relatively 'clean' and tractable.

What happens to a star when it is disrupted? Earlier investigations by, for instance, Lacy, Townes and Hollenbach 1982; Rees 1988; Evans and Kochanek 1989; Canizzo, Lee and Goodman 1990 are now being supplemented by more detailed numerical modelling (eg Khokhlov, Novikov and Pethick 1993; Frohlov *et al.* 1994; Deiner *et al.* 1997). The tidally disrupted star, as it moves away form the hole, develops into an elongated banana-shaped structure, the most tightly bound debris (the first to return to the hole) being at one end (Evans and Kochanek 1989; Laguna *et al.* 1993; Kochanek, 1994, Rees 1994). There would not be a conspicuous 'prompt' flare signalling the disruption event, because the thermal energy liberated is trapped within the debris. Much more radiation emerges when the bound debris (by then more diffuse and transparent) falls back onto the hole a few months later, after completing an eccentric orbit. The dynamics and radiative transfer are then even more complex and uncertain than in the disruption event itself, being affected by relativistic precession, as well as by the effects of viscosity and shocks (See Rees 1994, 1996 and earlier work cited therein)

The radiation from the inward-swirling debris would be predominantly ther-

mal, with a temperature of order 10^5 K; however the energy dissipated by the shocks that occur during the circularisation would provide an extension into the X-ray band. High luminosities would be attained – the total photon energy radiated (up to 10^{53} ergs) could be several thousand times more than the photon output of a supernova, though the bolometric correction could be much larger too. The flares would, moreover, not be standardised – what is observed would depend on the hole's mass and spin, the type of star, the impact parameter, and the orbital orientation relative to the hole's spin axis and the line of sight; perhaps also on absorption in the galaxy. To compute what happens involves relativistic gas dynamics and radiative transfer, in an unsteady flow with large dynamic range, which possesses no special symmetry and therefore requires full 3-D calculations – a worthy computational challenge to those who have many gigaflops at their disposal.

4.2 Can the 'flares' be detected?

Supernova-type searches with 10^4 galaxy-years of exposure should either detect flares due to this phenomenon, or else place limits on the mean mass of central black holes in nearby galaxies. This possible bonus should be an added incentive for such searches. It is not clear whether the best strategy involves monitoring nearby galaxies over a large area of sky or larger numbers of more remote galaxies. Large numbers of distant galaxies are, for instance, being routinely monitored by S. Perlmutter and colleagues in programmes aimed at discovering supernovae at redshifts of order 0.5. It would be surprising if such programmes did not detect such flares – a negative result will itself be interesting. However, if a 'flare' (with the expected duration of months) happened in a distant galaxy, one would not be able to check just how quiescent the galaxy had previously been. It would be easier to be sure that a detected flare was actually due to a disrupted star (and not just an upward fluctuation in the gaseous accretion rate) if it were observed in a closer galaxy that was known to have previously been inactive.

There has already been possible serendipitous detection of one transient event in the nucleus of a galaxy (Renzini *et al.* 1995), though its peak luminosity was far below what might be expected. X-ray surveys may also detect the events if (like AGNs) their spectra, though peaking in the UV, display a high-energy tail (Sembay and West 1993). The predicted flares offer a robust diagnostic of the massive holes in quiescent galaxies.

4.3 'Fossil events' in our Galactic Centre?

The rate of tidal disruptions in our Galactic Centre would be no more than once per 10^5 years. But each such event could generate a luminosity several times 10^{44} erg/s for about a year. Were this in the UV, the photon output, spread

over 10^5 years, could exceed the current ionization rate: the mean luminosity of the Galactic Centre might exceed the median value.

The resultant fossil ionization would set a lower limit to the electron density. The radiation emitted from the event might reach us after a delay if it were reflected off surrounding material. Churazov *et al.* (1994) have already used this argument to set a non-trivial constraint on the history of the Galactic Centre's X-ray output over the last few thousand years. Half the debris from a disrupted star would be ejected on hyperbolic orbits in a fan (which may intersect an orbiting disc in a line). The structure in the central 2 pc could be a single spiral feature (Lacy 1994). One speculative possibility (Rees 1987) is that this feature may be a 'vapour trail' created by such an event.

5 AGN demography and black hole formation

The quasar population peaks at redshifts between 2 and 3, but genuinely seems to be 'thinning out' at higher redshifts, corresponding to still earlier epochs: the comoving density of quasars falls by at least 3 for each unit increase in z beyond 3 (see Shaver, 1995 for a review). The impressive complementary strengths of HST and the Keck Telescope have revealed galaxies with the same range of high redshifts as the quasar population itself. Many of the faint smudges visible in the Hubble Deep Field (Williams etal 1996), the deepest picture of the sky ever obtained, are galaxies with redshifts of order 3, being viewed at (or even before) the era when their spheroids formed.

Considerations of AGN 'demography', by now well known, suggest that the ultraluminous quasar phase may have a characteristic lifetime set by the 'Eddington timescale' of 4×10^7 years, being associated with the formation of a black hole, or the immediate aftermath of this process. Straightforward arithmetic based on the observed numbers of quasars then implies (albeit with substantial numerical uncertainty because of the poorly known luminosity function, etc.) that most large galaxies could indeed have gone through a quasar phase; they would, in consequence, by $z = 2$ ($2-3$ billion years) have developed central holes of $10^6 - 10^9 M_\odot$.

Physical conditions in the central potential wells, when galaxies were young and gas-rich, should have been propitious for black hole formation. Infalling primordial gas would gradually condense into stars, forming the central spheroid of such systems. But star formation would be quenched when the gas reached some threshold central concentration: as the gas evolved (through loss of energy and angular momentum) to higher densities and more violent internal dissipation, radiation pressure would inevitably puff it up and inhibit further fragmentation (Rees, 1993, Haehnelt and Rees 1993). Much of whatever gas remains at this stage would then agglomerate into a massive hole.

This argument can be quantified, at least in a crudely approximate way. A differentially rotating self-gravitating gas mass can dissipate its energy (via non-

axisymmetric instabilities) on a dynamical timescale. Its internally-generated luminosity can then be expressed in terms of its virial velocity $v = (GM/r)^{1/2}$ as

$$L = v^5/G = 10^{59}(v/c)^5\,\mathrm{erg\,s^{-1}} \tag{1}$$

Note the straightforward analogy to the 'maximal power' c^5/G familiar to relativists and gravitational wave experimenters. This luminosity reaches the Eddington limit when v is high enough: the gas is then 'puffed up' by radiation pressure, and fragmentation is no longer possible. The criterion is

$$v > 300(M/10^6 M_\odot)^{1/5}\,\mathrm{km\ s^{-1}} \tag{2}$$

This criterion may be fulfilled for the entire gas mass, or for the inner part of a self-gravitating disc. Moreover, while sufficient, (2) is by no means necessary: fragmentation may be inhibited at a substantially earlier stage by the effects of higher opacity than electron scattering alone provides, or by magnetic stresses. If fragmentation is inhibited, collapse to a supermassive black hole seems almost inevitable. To evade such an outcome, either:

(i) Stars must form (before (2) is satisfied) with nearly 100 per cent efficiency; moreover, they must all have low mass (so that no material is expelled again) *or*

(ii) Gas must remain in a self-gravitating disc for hundreds of orbital periods, without the onset of any instability that redistributes angular momentum and allows the inner fraction to collapse enough to cross the threshold when (2) applies.

Neither of these 'escape routes' seems at all likely – the first would require the stars to have an initial mass function quite different from what is actually observed in the spheroids of galaxies; the second is contrary to well-established arguments that self-gravitating discs are dynamically unstable. The mass of the hole would depend on that of its host galaxy, though not necessarily via an exact proportionality: the angular momentum and the depth of the galaxy's potential well are relevant factors too.

This process involves complex gas dynamics and feedback from stars; we are still a long way from being able to make realistic calculations. At the moment, the most compelling argument that a massive black hole is an expected byproduct comes from the implausibility of the alternatives. The mass of the hole would depend on that of its host galaxy, though not necessarily via an exact proportionality: the angular momentum of the protogalaxy and the depth of its central potential well are relevant factors too. A more quantitative estimate depends on calculating in full detail when, during the progressive concentration towards the centre, star formation ceases (because of radiation pressure, magnetic fields, or whatever) and the remaining gas evolves instead into a supermassive object.

Once a large mass of gas became too condensed to fragment into stars, it would continue to contract and deflate. Some mass would inevitably be shed, carrying away angular momentum, but the remainder could continue contracting

until it underwent complete gravitational collapse. This could be a substantial fraction – for example, if 10 per cent of the mass had to be shed in order to allow contraction by a factor of 2, about 20 per cent could form a black hole.

Firmer and more quantitative conclusions will have to await elaborate numerical simulations. But on one issue I would already bet strongly. This is that a massive black hole forms directly from gas (some, albeit, already processed through stars), perhaps after a transient phase as a supermassive object, rather than from coalescence of stars or mergers of stellar-mass holes.

The energy radiated during further growth of the hole manifests itself as a quasar. The peak in the quasar population (i.e. redshifts in the range 2 - 3) signifies the era when large galactic spheroids were forming in greatest profusion. It is worth noting, incidentally, that whereas activity in low-z galaxies may be correlated with some unusual disturbance due to a tidal encounter or merger, this may not be the right way to envisage the more common high-z quasars. Any newly-formed galaxy is inevitably 'disturbed', in the sense that it has not yet had time to settle down and relax: no external influence is needed to perturb axisymmetry or to trigger a large inflow of gas.

6 Do the candidate holes obey the Kerr metric?

6.1 Probing the region near the hole

As already discussed in section 3, NGC 4258 offers the clearest evidence so far for a central dark mass. But the observed molecular disc lies a long way out: at around 10^5 gravitational radii. We can exclude all conventional alternatives (dense star clusters, etc); however, the measurements tell us nothing about the central region where gravity is strong, certainly not whether the putative hole actually has properties consistent with the Kerr metric. The stars in the central parts of M31 and our own galaxy likewise lie so far out that their orbits are essentially Newtonian.

The phenomena of AGNs are due to material closer to the central mass, but nobody could yet claim that any observed features of AGNs offers a clear diagnostic of a Kerr metric. All we can really infer is that 'gravitational pits' exist, which must be deep enough to allow several percent of the rest mass of infalling material to be converted into kinetic energy, and then radiated away from a region compact enough to vary on timescales as short as an hour. General relativity has been resoundingly vindicated in the weak field limit (by high-precision observations in the Solar System, and of the binary pulsar) but we still lack quantitative probes of the strongly relativistic region.

The tidal disruption events described in section 4 depend crucially on distinctive precession effects around a Kerr metric, but the gas dynamics are so complex and messy that even when a flare is detected it will not serve as a useful diagnostic of the metric in the strong-field domain. On the other hand,

the stars whose motions reveal a central dark mass in our Galactic Centre, in M31, and in other normal galaxies are in orbits $\gtrsim 10^5$ times larger than the putative holes themselves.

Relativists would seize eagerly on any relatively 'clean' probe of the relativistic domain. In most accretion flows, the emission is concentrated towards the centre, where the potential well is deepest and the motions fastest. Such basic features of the phenomenon as the overall efficiency, the minimum variability timescale, and the possible extraction of energy from the hole itself all depend on inherently relativistic features of the metric – on whether the hole is spinning or not, how it is aligned, etc. There are now several encouraging new possibilities.

6.2 X-ray spectroscopy of accretion flows

Optical spectroscopy tells us a great deal about the gas in AGNs. However, the optical inferences pertain to gas that is quite remote from the hole itself. This is because the innermost regions would be so hot that their thermal emission emerged as more energetic quanta: the optical observations sample radiation that is emitted (or at least reprocessed) further out. The X-rays, on the other hand, come predominantly from the relativistic region. Until recently, however, the energy resolution and sensitivity of X-ray detectors was inadequate to permit the study of line shapes. But this is now changing. The ASCA X-ray satellite was the first to offer sufficient spectral resolution to reveal line profiles, and therefore opened up the possibility of seeking the substantial gravitational redshifts, as well as large doppler shifts, that would be expected. (Fabian *et al.* 1989, and earlier references cited therein). There is already one convincing case (Tanaka *et al.* 1995) of a broad asymmetric emission line indicative of a relativistic disc viewed at $\sim 60^\circ$ to its plane, and others are now being found. The value of (a/m) can in principle be constrained too, because the emission is concentrated closer in, and so displays larger shifts, if the hole is rapidly rotating (Iwasawa *et al.* 1996).

The appearance of a disc around a hole, taking doppler and gravitational shifts into account, along with light bending, was calculated by Bardeen and Cunningham (1973) and by several other authors. The associated swing in the polarization vector of photon trajectories near a hole was also long ago suggested (Connors, Piran and Stark 1980) as another diagnostic; but this is still not feasible because X-ray polarimeters are far from capable of detecting the few per cent polarization expected.

6.3 Stars in relativistic orbits?

These X-ray observations are of course of Seyfert galaxies, whose centres, though not emitting as powerfully as quasars, are by no means inactive. But we still need a 'cleaner' and more quantitative probe of the strong-field regime.

A small star orbiting close to a supermassive hole would behave like a test particle, and its precession would probe the metric in the 'strong field' domain. These interesting relativistic effects, have been computed in detail by Karas and Vokrouhlicky (1993, 1994) and Rauch (1997). Would we expect to find a star in such an orbit?

An ordinary star certainly cannot get there by the kind of 'tidal capture' process that can create close binary star systems. This is because the binding energy of the final orbit (a circular orbit with radius $2r_T$, which has the same angular momentum as an initially near-parabolic orbit with pericentre at r_T) is far higher when the companion is a supermassive hole than when it is also of stellar mass – it scales roughly as $M^{2/3}$. This orbital energy would have to be dissipated within the star, and that cannot happen without destroying it: a star whose orbit brings it within (say) $3r_T$ of a massive black hole may not be destroyed on first passage (as described in section 4); however, is then on a bound elliptical orbit, it will surely be disrupted before the orbit has circularised. (It would then give a 'flare' similar to that discussed in section 4, but with a somewhat longer timescale.)

Syer, Clarke and Rees (1991) pointed out, however, that an orbit can be 'ground down' by successive impacts on a disc (or any other resisting medium) without being destroyed: the orbital energy then goes almost entirely into the material knocked out of the disc, rather than into the star itself. Other constraints on the survival of stars in the hostile environment around massive black holes – tidal dissipation when the orbit is eccentric, irradiation by ambient radiation, etc – are explored by Podsiadlowski and Rees (1994), and King and Done (1993).

These stars would not be directly observable, except maybe in our own Galactic Centre. But they might have indirect effects: such a rapidly-orbiting star in an active galactic nucleus could signal its presence by quasiperiodically modulating the AGN emission.

There was a flurry of interest some years ago when X-ray astronomers detected an apparent 3.4 hour periodicity in the Seyfert galaxy NGC 6814. But it turned out that there was a foreground binary star, with just that period, in the telescope's field of view. But theorists shouldn't be downcast. It is more elevated to make predictions than to explain phenomena a posteriori, and that's all we can now do. There is a real chance that someday observers will find evidence that an AGN is being modulated by an orbiting star, which could act as a test particle whose orbital precession would probe the metric in the domain where the distinctive features of the Kerr geometry should show up clearly.

6.4 Gravitational-wave capture of compact stars

Objects circling close to supermassive black holes could be neutron stars or white dwarfs, rather than ordinary stars. Such compact stars would be impervious to tidal dissipation, and would have such a small geometrical cross section

that the ‘grinding down’ process would be ineffective too. On the other hand, because they are small they can get into very tight orbits by straightforward stellar-dynamical processes. For ordinary stars, the ‘point mass’ approximation breaks down for encounter speeds above 1000 km/s – physical collisions are then more probable than large-angle deflections: but there is no reason why a ‘cusp’ of tightly bound *compact* stars should not extend much closer to the hole. Neutron stars or white dwarfs could exchange orbital energy by close encounters with each other until some got close enough that they either fell directly into the hole, or until gravitational radiation became the dominant energy loss. Gravitational radiation losses tend to circularise an elliptical orbit with small pericentre. Most stars in such orbits would be swallowed by the hole before circularisation, because the angular momentum of a highly eccentric orbit ‘diffuses’ faster than the energy does due to encounters with other stars, but some would get into close circular orbits (Hils and Bender 1995; Sigurdsson and Rees 1997).

A compact star is less likely than an ordinary star in similar orbit to ‘modulate’ the observed radiation in a detectable way. But the gravitational radiation (almost periodic because the dissipation timescale involves a factor $(M/m*)$) might eventually be detectable (see below).

6.5 The Blandford-Znajek process

Blandford and Znajek (1977) showed that a magnetic field threading a hole (maintained by external currents in, for instance, a torus) could extract spin energy, converting it into directed Poynting flux and electron-positron lairs. This is, in effect, an astrophysically-realistic example of the Penrose (1969) process whereby the spin of a Kerr hole can be tapped. It would indeed be exciting if we could point to objects where this was happening. The centres of galaxies display a bewildering variety of phenomena, on scales spanning many powers of 10. The giant radio lobes sometimes spread across millions of lightyears – 10^{10} times larger than the hole itself. If the Blandford-Znajek process is really going on (Rees *et al.* 1982) these huge structures may be the most direct manifestation of an inherently relativistic effect around a Kerr hole.

Jets in some AGNs definitely have Lorentz factors γ_j exceeding 10. Moreover, some are probably Poynting-dominated, and contain pair (rather than electron-ion) plasma. But there is still no compelling reason to believe that these jets are energised by the hole itself, rather than by winds and magnetic flux ‘spun off’ the surrounding torus. The case for the Blandford-Znajek mechanism would be strengthened if baryon-free jets were found with still higher γ_j , or if the spin of the holes could be independently measured, and the properties of jets turned out to depend on (a/m).

6.6 Scaling laws and 'microquasars'

Two of the galactic X-ray sources that are believed to involve black holes (See Table 1) generate double radio structures that resemble miniature versions of the classical extragalactic strong radio sources. The jets have been found to display apparent superluminal motions across the sky, indicating that, like the extragalactic radio sources, they contain plasma that is moving relativistically (Mirabel and Rodriguez 1994).

There is no reason to be surprised by this analogy between phenomena on very different scales. Indeed, the physics of flows around black holes is always essentially the same, apart from very simple scaling laws. If we define $l = L/L_{Ed}$ and $\dot{m} = \dot{M}/\dot{M}_{crit}$, where $\dot{M}_{crit} = L_{Ed}/c^2$, then for a given value of $\dot{m}$, the flow pattern may be essentially independent of M. Linear scales and timescales, at a given value of r/r_g, where $r_g = GM/c^2$, are proportional to M, and densities in the flow for a given $\dot{m}$ then scale as M^{-1}. The physics that amplifies and tangles any magnetic field may be scale-independent; the field strength B then scales as $M^{-1/2}$. So the bremsstrahlung or synchrotron cooling timescales (proportional to ρ^{-1} and $B^{-1/2}$ respectively) go as M, implying that t_{cool}/t_{dyn} depends primarily on $\dot{m}$. So also do the ratios involving, for instance, coupling of electron and ions in thermal plasma. Therefore, the efficiencies and the value of l are insensitive to M, and depend primarily on $\dot{m}$. Moreover, the form of the spectrum depends on M only rather insensitively (and in a manner that is easily calculated).

The kinds of accretion flow inferred in, for instance, M87, giving rise to a compact radio and X-ray source, along with a relativistic jet, could operate just as well if the hole mass was lower by a hundred million, as in the galactic LMXB sources. So we can actually study the processes involved in AGNs in microquasars close at hand within our own galaxy. And we may even be able to see the entire evolution of a strong extragalactic radio source, speeded up by a similar factor.

6.7 Discoseismology

Discs or tori that are maintained by steady flow into a black hole can support vibrational modes (Kato and Fukui 1980; Nowak and Wagoner 1992, 1993). The frequencies of these modes can, as in stars, serve as a probe for the structure of the inner disc or torus. The amplitude depends on the importance of pressure, and hence on disc thickness; how they are excited, and the amplitude they may reach, depends, as in the Sun, on interaction with convective cells and other macroscopic motions superimposed on the mean flow. But the *frequencies* of the modes can be calculated more reliably. In particular, the lowest g-mode frequency is close to the maximum value of the radial epicyclic frequency k. This epicyclic frequency is, in the Newtonian domain, equal to the orbital frequency. It drops to zero at the innermost stable orbit. It has a maximum at about

$9GM/c^2$ for a Schwarzschild hole; for a Kerr hole, k peaks at a smaller radius (and a higher frequency for a given M). The frequency is 3.5 times higher for $(a/m) = 1$ than for the Schwarzschild case.

Nowak and Wagoner pointed out that these modes may cause an observable modulation in the X-ray emission from galactic black hole candidates. Just such effects have been seen in GRS 1915+105 (Morgan *et al.* 1996). The amplitude is a few per cent (and somewhat larger at harder X-ray energies, suggesting that the oscillations involve primarily the hotter inner part of the disc). The fluctuation spectrum shows a peak in Fourier space at around 67 Hz. This frequency does not change even when the X-ray luminosity doubles, suggesting that it relates to a particular radius in the disc. If this is indeed the lowest g-mode, and if the simple disc models are relevant, then the implied mass is $10.2M_\odot$ for Schwarzchild, and $35M_\odot$ for a 'maximal Kerr' hole (Nowak *et al.* 1997). The mass of this system is not well known. However, this technique offers the exciting prospect of inferring (a/m) for holes whose masses are independently known.

GRS 1915+105 is one of the objects with superluminal radio jets. The simple scaling arguments of section 6.6 imply that the AGNs which it resembles might equally well display oscillations with the same cause. However, the periods would be measured in days, rather than fractions of a second.

7 Gravitational radiation as a probe

7.1 Gravitational waves from newly-forming massive holes?

The gravitational radiation from black holes, as Kip Thorne's paper emphasises, offers potentially impressive tests of general relativity, involving no physics other than the dynamics of spacetime itself.

At first sight, the original formation of the holes might seem the most obvious sources of strong wave pulses. However the wave emission would only be efficient if the holes formed on a timescale as short as (r_g/c) – something that might happen if they built up via coalescence of smaller holes (cf Quinlan and Shapiro 1990).

If, on the other hand, supermassive black holes formed as suggested in section 5 – directly from gas (some, albeit, already processed through stars), perhaps after a transient phase as a supermassive object – then the process would be too gradual to yield efficient gravitational radiation. The least pessimistic scenario from the perspective of gravitational-wave astronomers, in the context of these latter ideas, would be one in which a supermassive star accumulates, and then collapses into a hole, on a dynamical timescale, via post-Newtonian instability. But even this yields much weaker gravitational radiation than black hole coalescence. That is because post-Newtonian instability is triggered at a radius $r_i \gg r_g$. Supermassive stars are fragile because of the dominance of

radiation pressure: this renders the adiabatic index Γ only slightly above 4/3 (by an amount of order $(M/M_{\odot})^{-1/2}$). Since $\Gamma = 4/3$ yields neutral stability in Newtonian theory, even the small post-Newtonian corrections then destabilise such 'superstars'. The characteristic collapse timescale when instability ensues is longer than r_g/c by the 3/2 power of that factor, and the total gravitational wave energy emitted is lower by the cube. Efficiency might be enhanced if the specific angular momentum when the instability occurred were just above the limit that could be accepted by a newly-formed Kerr hole. Material falling inward would then accumulate in a disc or pancake structure with dimensions only a few times r_g; if ordinary viscosity were ineffective in expelling the excess angular momentum, the disc might then become sufficiently assymetric that gravitational waves could do the job.

If the material were initially of uniform density (a 'top hat' distribution) and then fell in freely, it would all reach the centre simultaneously. However, this would not happen if the pre-collapse density profile were characteristic of a supermassive object. Different shells of material would reach the centre at times spread by roughly the initial free-fall time, larger than (r_g/c) by a factor $(r_i/r)^{3/2}$. (In the spherical case, r_i/r_g would be $(M/M_{\odot})^{1/2}$). If other mechanisms for angular momentum transfer could be suppressed, the resultant ring of material would swirl inward, owing to loss of angular momentum via gravitational radiation, in $(M_{ring}/M)^{-1}$ orbital periods. A quasi-steady state could therefore be maintained for the overall-free fall timescale $\sim (r_i/r)^{3/2}(r_g/c)$, during which material drains inward so that the amount stored in the ring maintains itself at $(r_i/r)^{-3/4}M$. The gravitational radiation would be 'efficient' in the sense that it carried away a significant fraction of the rest-mass energy, but this would happen over a longer period than r_g/c, so the amplitude would be lower by $(r_i/r)^{-3/4}$. (I should emphasise that this example is merely illustrative, and is obviously not very realistic.)

The important point is that the formation of a hole 'in one go' from a supermassive star is an unpromising source of gravitational waves. If the hole grows more gradually, then the prospects are obviously still worse. On the other hand, if the host galaxy had not yet acquired a well-defined single centre, several separate holes could form, and yield strong events when they subsequently coalesce.

The gravitational waves associated with supermassive holes would be concentrated in a frequency range around a millihertz – too low to be accessible to ground-based detectors, which lose sensitivity below 100 Hz, owing to seismic and other background noise. Space-based detectors are needed. One such, proposed by the European Space Agency, is the Laser Interferometric Spacecraft (LISA) – six spacecraft in solar orbit, configured as two triangles, with a baseline of 5 million km whose length is monitored by laser interferometry.

7.2 Coalescing supermassive holes.

The guaranteed sources of really intense gravitational waves in LISA's frequency range would be coalescing supermassive black holes. Many galaxies have experienced a merger since the epoch $z > 2$ when, according to 'quasar demography' arguments (section 3) they acquired central holes. The holes in the two merging galaxies would spiral together, emitting, in their final coalescence, up to 10 per cent of their rest mass as a burst of gravitational radiation in a timescale of only a few times r_g/c. These pulses would be so strong that LISA could detect them with high signal-to-noise even from large redshifts. Whether such events happen often enough to be interesting can to some extent be inferred from observations (we see many galaxies in the process of coalescing), and from simulations of the hierarchical clustering process whereby galaxies and other cosmic structures form. Haehnelt (1994) calculated the merger rate of the large galaxies believed to harbour supermassive holes: it is only about one event per century, even out to redshifts $z = 4$. Mergers of small galaxies are more common – indeed big galaxies are probably the outcome of many successive mergers. We have no direct evidence on whether these small galaxies harbour black holes (nor, if they do, of what the hole masses typically are). However it is certainly possible that enough holes of (say) $10^5 M_\odot$ lurk in small early-forming galaxies to yield, via subsequent mergers, more than one event per year detectable by LISA.

7.3 Effects of recoil

There would be a recoil due to the non-zero net *linear* momentum carried away by gravitational waves in the coalescence. If the holes have unequal masses, a preferred longitude in the orbital plane is determined by the orbital phase at which the final plunge occurs. For spinning holes there may be a rocket effect perpendicular to the orbital plane, since the spins break the mirror symmetry with respect to this plane. (Redmount and Rees, 1989 and references cited therein.)

The recoil is a strong-field gravitational effect which depends essentially on the lack of symmetry in the system. It can therefore only be properly calculated when fully 3-dimensional general relativistic calculations are feasible. The velocities arising from these processes would be astrophysically interesting if they were enough to dislodge the resultant hole from the centre of the merged galaxy, or even eject it into intergalactic space.

LISA is potentially so sensitive that it could detect the nearly-periodic waves waves from stellar-mass objects orbiting a $10^5 - 10^6 M_\odot$ hole, even at a range of a hundred Mpc, despite the m/M factor whereby the amplitude is reduced compared with the coalescence of two objects of comparable mass M. The stars in the observed 'cusps' around massive central holes in nearby galaxies are of course (unless almost exactly radial) on orbits that are far too large to display relativistic effects. Occasional captures into relativistic orbits can come about by

dissipative processes – for instance, interaction with a massive disc (eg Canizzo, Lee and Goodman 1990; Syer, Clarke and Rees 1991). But unless the hole mass were above $10^8 M_\odot$ (in which case the waves would be at too low a frequency for LISA to detect), solar-type stars would be tidally disrupted before getting into relativistic orbits. Interest therefore focuses on compact stars, for which dissipation due to tidal effects or drag is less effective. As described in section 6.3, compact stars may get captured as a result of gravitational radiation, which can gradually 'grind down' an eccentric orbit with close pericenter passage into a nearly-circular relativistic orbit (Hils and Bender 1995; Sigurdsson and Rees 1996). The long quasi-periodic wave trains from such objects, modulated by orbital precession (cf Karas and Vokrouhlicky 1993; Rauch 1997), in principle carry detailed information about the metric.

The attraction of LISA as an 'observatory' is that even conservative assumptions lead to the prediction that a variety of phenomena will be detected. If there were many massive holes not associated with galactic centres (not to mention other speculative options such as cosmic strings), the event rate could be much enhanced. Even without factoring in an 'optimism factor' we can be confident that LISA will harvest a rich stream of data.

LISA is at the moment just a proposal – even if funded, it is unlikely to fly before 2017. (It will cost perhaps 3 times as much as LIGO Phase 1, but may detect infinitely more events). Is there any way of learning, before that date, something about gravitational radiation? The dynamics (and gravitational radiation) when two holes merge has so far been computed only for cases of special symmetry. The more general problem – coalescence of two Kerr holes with general orientations of their spin axes relative to the orbital angular momentum – is one of the US 'grand challenge' computational projects. When this challenge has been met (and it will almost certainly not take all the time until 2017) we shall find out not only the characteristic wave form of the radiation, but the recoil that arises because there is a net emission of linear momentum.

This recoil could displace the hole from the centre of the merged galaxy (Valtonen 1996 and references therein) – it might therefore be relevant to the low-z quasars that seem to be asymmetrically located in their hosts (and which may have been activated by a recent merger). Even galaxies that do not harbour a central hole may, therefore, once have done so in the past. The core of a galaxy that has experienced such an ejection event may retain some trace of it (perhaps, for instance, an unusual profile), because of the energy transferred to stars via dynamical friction during the merger process (cf Ebisuzaki, Makino and Okumura 1991; Faber *et al.* 1997).

The recoil might even be so violent that the merged hole breaks loose from its galaxy and goes hurtling through intergalactic space. This disconcerting thought should impress us with the reality and 'concreteness' of the entities whose theoretical properties Chandra did so much to illuminate.

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Table I

Stellar-mass black hole candidates and their binary companions

	$M_h/M_\odot$	$M_*/M_\odot$
High mass companions		
Cyg X1	11-21	24-42
LMC X3	5.6-7.8	20
Low mass companions (X-ray transients)		
V404 Cyg	10-15	~ 0.6
A 0620-00	5-17	0.2-0.7
Nova Muscae	4.2-6.5	0.5-0.8
GS 2000+25	6-14	~ 0.7
GROJ1655-40	4.5-6.5	~ 1.2
N. Oph 77	5-9	~ 0.4
J0422432	6-14	~ 0.3

Table II

Supermassive holes

	$M_h/M_\odot$	Method
M87	2.10^9	stars+opt.disc
NGC 3115	10^9	stars
NGC 4486 B	5.10^8	stars
NGC 4594 (Sombrero)	5.10^8	stars
NGC 3377	8.10^7	stars
NGC 3379	5.10^7	stars
NGC 4258	4.10^7	masing H_2O disc
M31 (Andromeda)	3.10^7	stars
M32	3.10^6	stars
Galactic Centre	$2.5.10^6$	stars+(3-D motions)